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A DETERMINATION OF THE PARAMETERS OF THE VENUSIAN ATMOSPHERE AT THE AVERAGE SURFACE LEVEL FROM RADIOASTRONOMICAL AND RADAR MEASUREMENTS

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A DETERMINATION OF THE PARAMETERS OF THE VENUSIAN ATMOSPHERE AT THE AVERAGE SURFACE LEVEL FROM RADIOASTRONOMICAL AND RADAR MEASUREMENTS

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Three independent estimates have been made of conditions in the lower Venusian atmosphere on the basis of results of radioastronomical measurements of the brightness temperature spectrum, polarization and radar reflection cross section and measurement data from the "Venus 4, 5 and 6" space probes. These estimates lead to two internally consistent models: an adiabatic model with $f_{H_2O} = 0.005$, $p_s = 65 \pm 20$ atm, $T_s = 700 \pm 50$°K and an isothermal model with $f_{H_2O} = 0$, $T_s = 650$°K, $p_s = 100 \pm 20$ atm. It is shown that the water vapor content in the atmosphere is nearer the lower limit, measured by the "Venus" series of probes, than the upper limit. The water content in the cloud layer is estimated.

In 1967 the "Venus 4" space probe made the first direct measurements of the temperature, pressure and density in the Venusian atmosphere and the distribution of these parameters with altitude during a descent 28 km in length [1]. "Venus 5 and 6" confirmed the results of these measurements and extended the measured region downward by 7 km [2]. On the other hand, radio-eclipse measurements, made with the American "Mariner 5" space probe [3], gave the altitude distribution of these parameters at higher altitudes. To sum up, the T(h) and p(h) distribution has been obtained within an altitude range of h ~ 50 km, and temperature variations from 240 to 600°K and pressure variations from 0.03 to 27 atm have been measured.

However, the measurements of the "Venus 5 and 6" space probes ceased at an altitude of ~20 km [2] above the average planet surface at the position of the descent of these probes. The "Mariner 5" measurements, in principle, could not be reduced to the planet's surface since the atmosphere below the level corresponding to a pressure of ~5 atm is inaccessible to the radio-eclipse method of investigation because of superrefraction. The surface and near-surface atmosphere was measured only in radioastronomical and radar observations of Venus.

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* Numbers in the margin indicate pagination in the foreign text.

In addition, measurements by means of descent probes encompass only a small localized region of the planet within the descent area, in which the atmosphere parameters can differ from the average values typical for the entire planet as a whole. However, the terrestrial radioastronomical and radar measurements are averaged for the entire visible hemisphere or for a large portion of the planet. Therefore a combination of the space and terrestrial measurements and a combined analysis of their results are mutually beneficial to the terrestrial as well as the space measurements. In particular, the measurement data of the "Venus 4, 5 and 6" probes make it possible to estimate, on the basis of the terrestrial radioastronomical and radar measurements of Venus, the temperature and pressure of the atmosphere at the average surface, as well as the water content in the atmosphere and in the cloud layer. /147

The first such estimate of the pressure at the surface was made in [4] on the basis of "Venus 4" data [1, 5] and led to an atmospheric pressure of 50-70 atm at the average surface. The result obtained was confirmed in [6-8]. The present paper contains a more complete and detailed analysis of the radioastronomical and radar measurements on the basis of data from the "Venus 5 and 6" probes [2, 9]. The initial parameters are the chemical composition of the atmosphere and the altitude distribution of the temperature and pressure, measured by the "Venus 4, 5 and 6" probes. It is assumed that the atmosphere is spherically symmetrical, and the surface is isothermal and uniform with a dielectric constant of $\varepsilon = 4.7 \pm 0.5$ [10]. The purpose of the analysis is a determination of the average surface level and the temperature and pressure of the atmosphere at this level, for which the atmosphere model best agrees with the data of radioastronomical and radar measurements.

In these measurements we analyzed three independent characteristics: the brightness temperature averaged over the visible disk and its wavelength dependence $\bar{T}_{b♀}(\lambda)$, the radio emission polarization and the effective radar reflection cross section and its wavelength dependence $\sigma_e(\lambda)$. Accordingly, below we discuss three independent methods of determining the atmosphere parameters at the average surface.

1) Analysis of $\bar{T}_{b♀}(\lambda)$ measurements. The method is based on determination of the surface temperature T_s from the data of radioastronomical measurements. Below the level at which the "Venus 5 and 6" probe measurements ceased the atmosphere was assumed to be adiabatic. The pressure p_s at the surface was calculated from the equation of state.

The surface temperature T_s is related to the measured brightness temperature $\bar{T}_{b♀}$, averaged over the visible disk, by the expression

$$\bar{T}_{b♀} = T_s I_1(\varepsilon, \tau) + \bar{T}_a, \quad (1)$$

where $I_s(\varepsilon, \tau)$ is the emissivity of the planet's surface, averaged over the visible disk, with atmosphere attenuation taken into account (see Table 2 in [11]), $\bar{T}_a$ is the component of the brightness temperature caused by atmosphere radiation. $\bar{T}_a$ was calculated from the formula

$$\bar{T}_b = 2 \int_0^1 \int_h^\infty T(h)\gamma(h)e^{-\tau(h)/\mu}\, dh\, d\mu. \qquad (2)$$

Here T(h) and γ(h) are the temperature and absorption coefficient of the atmosphere at altitude h, $\tau(h) = \int_h^\infty \gamma(h)\, dh, \sqrt{1-\mu^2}$ — is the distance from the center of the disk as a function of the planet radius. It was assumed that the attenuation of radio waves in the Venusian atmosphere beyond the cloud layer is determined only by molecular absorption and the corresponding coefficient is expressed by the following terms:

$$\gamma(h) = \gamma_{CO_2} + \gamma_{H_2O}.$$

The absorption coefficient of carbon dioxide is determined from the semi-empirical formula of Ho, Kaufman and Thaddeus [12] /148

$$\gamma_{CO_2} = (15.7 f_{CO_2}^2 + 3.9 f_{CO_2} f_{N_2} + 2.64 f_{CO_2} f_A + 0.085 f_{N_2}^2) \frac{1}{\lambda^2} \left(\frac{p}{760}\right)^2 \left(\frac{273}{T}\right)^5 \cdot 10^{-3} \ (км^{-1}), \qquad (3)$$

where p is the pressure in mm of mercury, λ is the wavelength in cm.

Since Ho, Kaufman and Thaddeus give values of the water vapor absorption coefficient γ_{H_2O} that are too small compared with the corresponding quantum-mechanical values* (and the latter agree well or, in certain portions of the spectrum , even lie somewhat below the experimental values for the earth's atmosphere**), in the calculations of the quantity γ_{H_2O} we used the quantum-mechanical formula

* For example, at a wavelength of 3 cm for a pressure of 62 atm, a temperature of 695°K and f_{H_2O} = 0.005 this discrepancy amounts to a factor of 1.7.

**See, for example, [13 concerning the matching of the calculated and measured values of γ_{H_2O} in the earth's atmosphere.

$$\gamma_{H_2O} = \left\{2.309\cdot 10^4 \left| e^{-\frac{642.219}{T}} - e^{-\frac{643.283}{T}} \right| \times \frac{\Delta\nu}{(0.5476 - 1/\lambda^2)^2 + 4(\Delta\nu)^2 \frac{1}{\lambda^2}} + 1.577\cdot 10^3 \frac{p}{760}\frac{1}{T}\right\} \frac{\rho}{\lambda^2 T^{1.5}} \ (\text{км}^{-1}). \tag{4}$$

Here, $\Delta\nu = 0.1493 \frac{p}{760}\left(\frac{T}{300}\right)^{-0.626}$ (cm^{-1}) is the half-width of the 5_{-1}-6_{-5} water vapor line, ρ is the absolute humidity in g/m^3, $\rho = 288.9 f_{H_2O} \frac{p}{T}$.

Equation (4) is obtained from Eq. (8) of [14] if the long-wavelength rotational transition of the H_2O molecule, centered at $\lambda = 1.35$ cm, is specially isolated in it, and the contribution of all other lines of the rotational spectrum of H_2O in the millimeter and centimeter bands is approximated in the form of a nonresonance term. The error of this approximation, even in the short-wavelength region of the millimeter band ($\lambda \simeq 4$ mm), does not exceed ~ 3%. In Eq. (4) consideration is given to the fact that the dipole moment of the H_2O molecule amounts to 1.88 db [15], and it is assumed that H_2O-CO_2 collisions are more effective for broadening the water vapor line than H_2O-N_2 collisions by a factor of 1.6 [16, 17].

Equation (4) is valid only for binary molecular collisions. At high pressures the probability of multiple collisions increases. However, estimates show that Eq. (4) is applicable, with sufficient accuracy, for calculations of the water vapor absorption coefficient in a moist carbon dioxide atmosphere even for pressures of ~100 atm. In fact, the ratio of the collision time of H_2O-CO_2 molecules (a dipole-quadrupole interaction, the interaction energy is inversely proportional to the fourth power of the distance between the molecules) to the time between collisions at temperatures of 650-700°K and pressures of ~ 100 atm amounts to ~ 0.15, i.e., this ratio is less than unity. This confirms the predominance of binary collisions of molecules even under these conditions.

At the same time at altitudes of about 100 km the ratio of the Doppler broadening (see Eq. (13.2) in [18]) to the half-width of the H_2O spectral line, caused by molecular collisions, amounts to $\Delta\nu_D/\Delta\nu \simeq 2.6\cdot 10^{-2}$. This fact, in conjunction with the comments made above, confirms the fact that Eq. (4), in which the influence of the Doppler effect on the shape and width of the spectral line is ignored, is valid within the entire range of altitudes considered, which give a noticeable contribution to the optical thickness of the Venusian atmosphere in the radio band at $\lambda > 0.4$ mm. /149

We have calculated $\bar{T}_{b♀}(\lambda)$ in the wavelength interval from 0.4 to 20 cm. At shorter wavelengths of the millimeter band the effect of the upper Venusian atmosphere is considerable, and it is necessary to have more precise data on the structure of the atmosphere above the cloud. The calculation of $\bar{T}_{b♀}$ was done on a computer. It was assumed that the relative amount of CO_2 in the planet's atmosphere is 0.95, and the amount of nitrogen and argon does not exceed 0.5. The relative water vapor content was varied within the limits $f_{H_2O} = 0\text{–}0.01$.

The desired quantities were the average surface level and the temperature at this level, for which the calculation best agrees with the radioastronomical measurements of $\bar{T}_{b♀}(\lambda)$. An analysis showed that best agreement occurs for a surface temperature of 705 ± 30°K and a pressure of $p_s = 66^{+20}_{-15}$ atm. The altitude of the level, corresponding to a pressure of 1 atm and adopted as the "zero" level by us below, above the average surface in this case amounts to $h_0 = 46.5 \pm 4$ km.

The results of the $\bar{T}_{b♀}(\lambda)$ calculation for this value of T_s are shown in Fig. 1. This same figure also shows all the known results of the radioastronomical measurements of $\bar{T}_{b♀}$ within the 0.3-20 cm wavelength band. The weighted mean values of $\bar{T}_{b♀}$, from measurements available in each band, are also given in the 3, 10 and 20-cm bands.

The good agreement of the calculation for $f_{H_2O} \leq 0.005$ with experiment at wavelengths $\lambda < 3$ cm, where $\bar{T}_{b♀}$ is determined primarily by the atmosphere parameters, confirms the conclusion that the carbon dioxide gas is the principal absorbing agent, determining the observed shape of the $\bar{T}_{b♀}(\lambda)$ spectrum.

The agreement of the experimental data with calculations eliminates the necessity of including any additional hypothetical substances, absorbing the short-wavelength radio emission. Furthermore, it can be stated that the amount of these substances cannot be large, and one can estimate the possible upper content limits. /150

Of the detected and probable components of the Venusian atmosphere, water vapor and water can be possible agents for absorbing microwave radiation.

Figure 1 shows, however, that 1% water vapor (throughout the entire extent of the atmosphere) agrees poorly with the data of radioastronomical measurements. However, better agreement of the calculation with experiment occurs for $f_{H_2O} = 0.1\%$. Thus, the radioastronomical measurements confirm that the water vapor content in the Venusian atmosphere is closer to the lower (0.1%) than to the upper (1%) limit, determined from the "Venus" series of space probe measurements.

In view of the detection of water vapor in the Venusian atmosphere it is reasonable to assume that the cloud layer is formed from water droplets and ice crystals. A calculation of the effect of absorption in the water droplets on the $\bar{T}_{b♀}(\lambda)$ spectrum makes it possible to estimate the upper limit of the water component of the Venusian clouds.

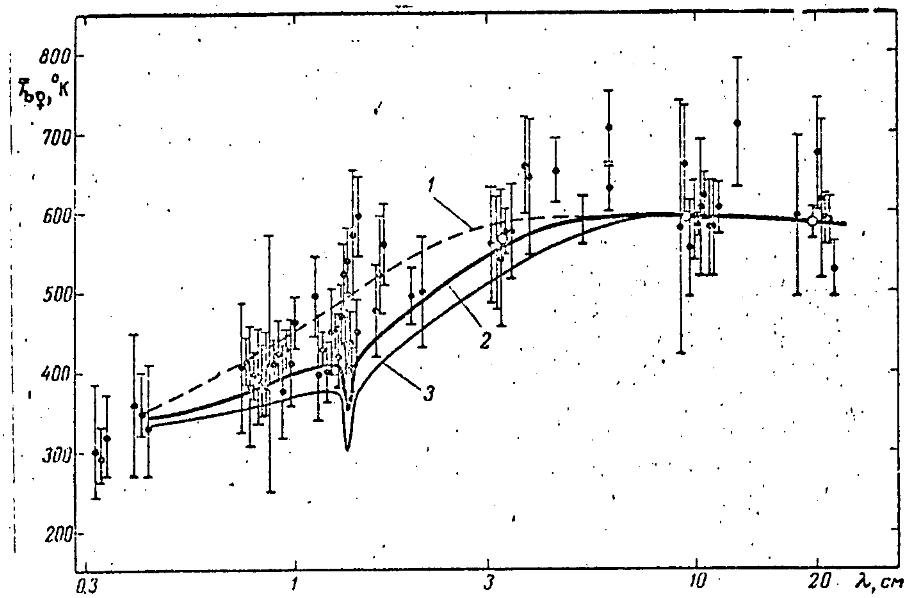


Figure 1. Measured and calculated $\bar{T}_{b♀}(\lambda)$ function for adiabatic lower atmosphere with $f_{CO_2} = 0.95$ and: 1) $f_{H_2O} = 0$; 2) $f_{H_2O} = 0.005$; 3) $f_{H_2O} = 0.01$ for $T_s = 705$°K.

The absorption coefficient of water droplets is calculated from the formula

$$\gamma_w = \frac{a(T)M_0}{\lambda^2}, \tag{5}$$

where M_0 is the water content of the cloud, a(T) is a temperature-dependent coefficient determined by the dielectric constant and relaxation time of a polar liquid. In the 250-300°K temperature interval this dependence can be approximated by the expression

$$\tau_{cloud} = \frac{2.23}{\lambda^2} B. \tag{6}$$

Here

$$B = \int_{h_1} M_0 e^{0.04[273-T(h)]}\, dh.$$

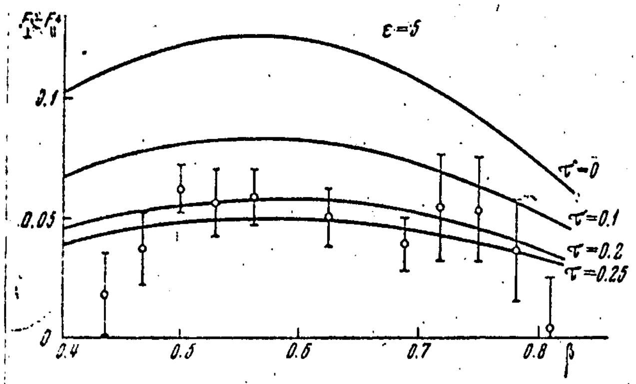
A calculation of $T_{b♀}(\lambda)$, made by us [4] for an atmosphere with a water cloud layer for B = 0.1, 0.3, 1 and 3 g/cm², agreed with experiment for B ≤ 0.3 g/cm².

2. Analysis of the polarization measurements. This method is based on a determination of the absorption and the pressure in the Venusian atmosphere inducing it, at which the differential polarization of the radio emission of Venus, measured in [19], agrees with a calculation.

It has been established [19] by radioastronomical polarization measurements that the high-temperature emission of Venus in the 10-cm band originates primarily from the hot surface of the planet. However, the amount of polarization of this emission was found to be less than can be expected for a dielectric constant, determined from radioastronomical measurements, of $\varepsilon = 4.7$ for the surface material, and resulted in a somewhat lower value of $\varepsilon = 2.5$, ignoring the effect of the atmosphere. Taking account of absorption in the atmosphere, which is significant at high pressures even in the 10-cm band and reduces the surface emission, this discrepancy can be explained. Furthermore, after determining the amount of absorption in the atmosphere, for which the calculated polarization value agrees with the measured, one can estimate, on the basis of the formulas given above, the value of the pressure corresponding to it and, consequently, the temperature of the atmosphere at the average surface level and the altitude of this level. /151

To compare with the results of the measurements of [19], we calculated the difference of the visibility functions in polarizations perpendicular $F_{\perp}$ and parallel $F_{\parallel}$ to the base of the radio interferometer. Unlike a similar calculation in [20], we adopted as a starting point the atmosphere parameters obtained as a result of the direct measurements of the "Venus 4, 5 and 6" probes. Below the level at which measurements ceased the atmosphere was assumed to be adiabatic. We also took account of the sphericity of the atmosphere, which is important near the edge of the disk, where the contribution of polarized radiation is especially large, as well as the effect of surface irregularities. In view of the fact that the nonisothermal character of the surface has little effect on the difference $F_{\perp} - F_{\parallel}$ of the visibility functions in the two polarizations, $F_{\perp}$ and $F_{\parallel}$ were calculated for an isothermal surface. The results of the calculation for $\varepsilon = 5$ and surface levels, corresponding to $\tau = 0$, 0.1, 0.2 and 0.25 at a wavelength of 10.6 cm for an adiabatic model, are shown in Fig. 2. Similar calculations have also been made for $\varepsilon = 3$ and 4. From a comparison of the calculation with experiment by the least-squares method, we determined the combinations of τ and ε that best correspond to the results of the measurements of [19]. In view of the fact that $d\tau/d\varepsilon < d\varepsilon/d\tau$ in the $\tau(\varepsilon)$ relationship determined in this fashion (Fig. 3) and, moreover, the quantity ε is determined from radar measurements, it was more expedient to specify ε and to determine τ. From the optimal $\tau(\varepsilon)$ relationship determined by us, we find that $\varepsilon = 4.7 \pm 0.5$ leads to $\tau_{\lambda = 10.6} = 0.22 \pm 0.03$.

The analysis that has been made and the estimates obtained are based on representing the planet's surface by a smooth sphere. The effect of surface irregularities reduces the difference $F_{\perp} - F_{\parallel}$ of the visibility functions and, consequently, the value of τ necessary for agreement of calculation and experiment. A calculation of the effect of the irregularities, similar to that conducted in [19], resulted in corrections of $\Delta\tau_1 = -0.035$, for $\varepsilon = 4.7$, at irregularities that are small-scale compared with the wavelength and $\Delta\tau_2 = -0.005$ at large-scale deviations of the surface from a sphere. Both of these corrections reduce the



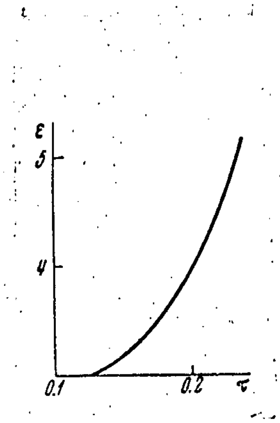


Figure 2. Difference $F_{\perp} - F_{\parallel}$ of visibility functions for $\varepsilon = 5$ and different values of the optical thickness of the atmosphere.

Figure 3. $\tau(\varepsilon)$ relationship that best matches the data of the measurements of [19].

optical thickness of the atmosphere, determined by us, to $\tau = 0.18 \pm 0.03$ at a wavelength of 10.6 cm. For an atmosphere containing 95% CO_2 and 0.5% water vapor, this value of τ in the adiabatic model corresponds to an atmosphere pressure of $p_s = 60 \pm 10$ atm at the average surface, a temperature of $T_s = 690 \pm 20$°K /152
and an altitude of $h_0 = 44 \pm 3$ km above the average surface for the zero level.

The parameters obtained correspond to $\tau_{\lambda = 3.1} = 1.54$, which also agrees well with the results of a measurement, made in 1967, of the polarization of the Venusian radio emission at a wavelength of 3.1 cm [21].

3. Analysis of $\sigma_e(\lambda)$ measurements. Yet another independent estimate of the pressure in the Venusian atmosphere is made on the basis of an analysis of the effective radar reflection cross section $\sigma_e(\lambda)$ of Venus. As is known, a typical feature of the measured $\sigma_e(\lambda)$ spectrum is the nearly constant value of σ_e in the wavelength interval from 70 to 20 cm and the sharp decrease at shorter wavelengths (by about a factor of 10 at a wavelength of 3.8 cm). The induced absorption in a dense CO_2 atmosphere must also reduce σ_e as the wavelength becomes shorter, with the amount of the reduction being a function of the pressure. As a result we have formulated a question: can the measured $\sigma_e(\lambda)$ function be explained by the absorption of microwave radiation in a CO_2 Venusian atmosphere and if so, then what must the pressure in the planet's atmosphere be ?

The quantity $\sigma_e(\lambda)$ was calculated from the formula

$$\sigma_e(\lambda) = \sigma_{e0} e^{-2\tau(\lambda)}, \qquad (7)$$

where σ_{e0} is the effective reflection cross section at $\lambda > 20$ cm, assumed equal to 0.14. To explain the decrease in σ_e at $\lambda = 3.8$ cm by absorption in the Venusian atmosphere, the optical thickness of the atmosphere at this wavelength must be equal to $\tau_{\lambda=3.8} = 1.1 \pm 0.1$. The $\tau(\lambda)$ relationship was determined by Eqs. (3) and (4). We note that when water vapor is present in the atmosphere, the frequency dependence of $\tau(\lambda)$ differs from $\propto \lambda^2$, assumed in [7 and 20]. Thus, for $f_{H_2O} = 0.005$ and $\tau_{\lambda=3.8} = 1.1$ a calculation from Eqs. (3) and (4) leads to $\tau = 0.18$ at $\lambda = 10.6$ cm instead of $\tau = 0.16$ for $\tau \propto \lambda^2$.

A comparison of the $\sigma_e(\lambda)$ calculation with experiment, presented in Fig. 4, shows that they agree well. For $\tau_{\lambda=3.8} = 1.1 \pm 0.1$, which serves as the basis of this calculation, this makes it possible to determine a pressure of $p_s = 58 \pm 6$ atm at the average surface. The atmosphere is also assumed to be adiabatic, containing 95% CO_2 and 0.5% water vapor. The pressure value obtained corresponds to a temperature $T_s = 685 \pm 20$°K and to a zero-level altitude of $h_0 = 44 \pm 2$ km.

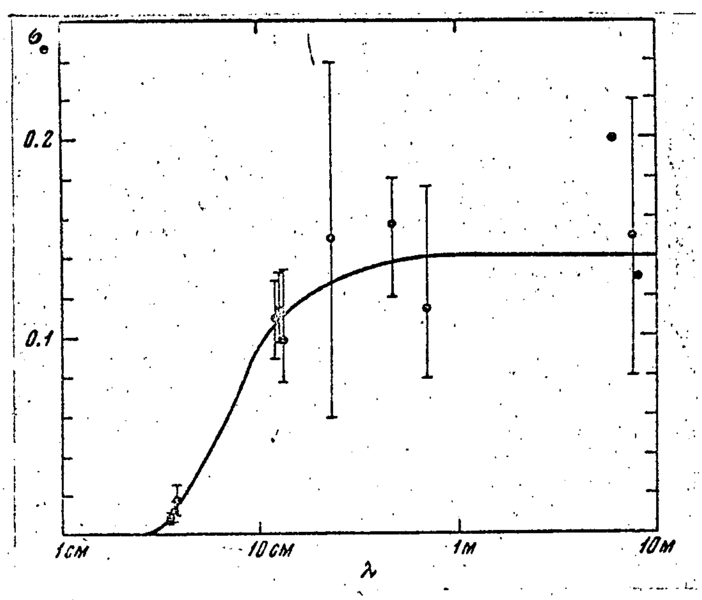


Figure 4. Measured and calculated $\sigma_e(\lambda)$ relationship for $f_{H_2O} = 0.005$.

Thus, the three independent estimates give results that agree well within the error limits, according to which the atmosphere pressure and temperature at the average surface level are equal to $p_s = 65 \pm 20$ atm and $T_s = 700 \pm 50$°K. The altitude of the zero level above the average surface is 45 ± 5 km in this model. /153

4. Other models of the lower Venusian atmosphere. The estimates that have been given above have been obtained under the assumption that the relative water vapor content, measured by the "Venus 4, 5 and 6" probes at a level corresponding to a pressure of about 1 atm, remains constant down to the surface. Such an assumption, however, is not obvious. The point is that in the Venusian atmosphere water cannot exist in the liquid phase below a level corresponding to a temperature of 430°K and a pressure of 5.5 atm. Therefore water vapor is not formed at the surface, as occurs on Earth, but at a fairly high altitude above the planet's surface. One can expect that the relative water vapor content will be a maximum near this level and will decrease above and below it. The transfer of water vapor into the near-surface region of the atmosphere can occur because of convection. However, for a subadiabatic and, even more, for an isothermal state of the near-surface atmosphere, there can be no convection in this region and the relative water vapor content will be considerably less. A decrease in the water vapor content in the lower atmosphere reduces the absorption of microwave radiation, and therefore to realize $\tau_{\lambda = 10.6} = 0.18 \pm 0.03$ and $\tau_{\lambda = 3.6} = 1.1 \pm 0.1$, corresponding to the radioastronomical and radar polarization measurements of $\sigma_e(\lambda)$, respectively, a greater atmosphere depth and higher pressure are necessary. In this case the estimates of p_s and T_s from the $\overline{T}_{b♀}(\lambda)$ spectrum, from polarization and from radar measurements are still closer together.

In the calculations made above, it was assumed that below the level at which "Venus 5 and 6" measurements ceased, the Venusian atmosphere is adiabatic. However, no direct measurements were made in this region. When, however, some agent is present in the lower atmosphere that absorbs solar radiation, one /154
can expect a decrease in the temperature gradient until the appearance of the isothermal region at the surface. Therefore we have also considered other models in which the lower Venusian atmosphere was assumed to be subadiabatic and even with an isothermal near-surface layer. In these models the surface temperature is lower than in the adiabatic model. Therefore for agreement with the radioastronomical measurements the near-surface atmosphere must make a large contribution to the radio emission of the planet, i.e., it must have a greater thickness than in the adiabatic model and, consequently, a higher pressure. This is illustrated in Fig. 5 in which are shown the results of a calculation of $\overline{T}_{b♀}(\lambda)$ for a model with an isothermal near-surface layer with $T = T_s = 650$°K. As should be expected, for a pressure of $p_s = 60$ atm, corresponding to the adiabatic model considered above, there is quite good agreement between calculation and experiment. Best agreement occurs for $p_s \geq 100$ atm. On the other hand, the replacement of the adiabatic model in the near-surface region by an isothermal one causes little change in the pressure value from the polarization and radar measurements, according to which $p_s = 60$ atm for $f_{H_2O} = 0.005$. Therefore in this model with the atmosphere composition assumed above it is impossible to achieve satisfactory agreement of the pressure estimate by these three methods.

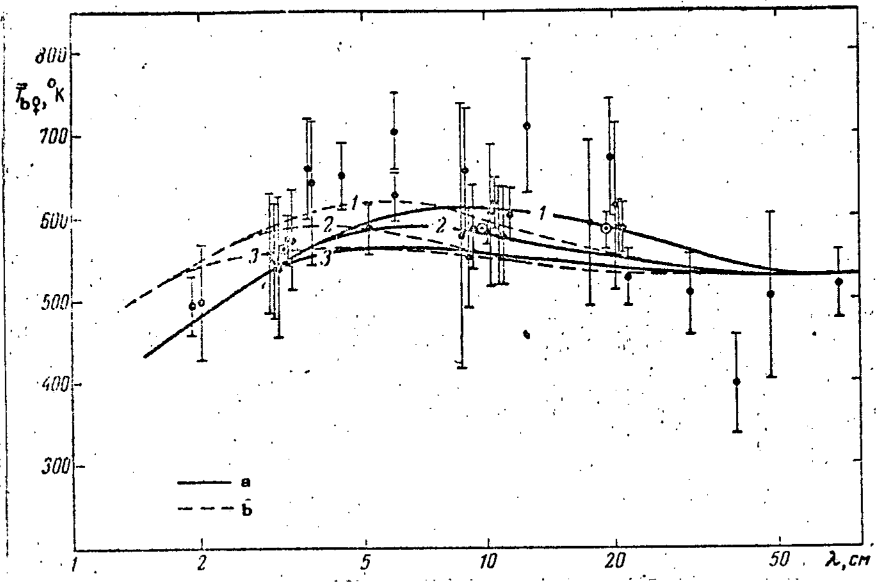


Figure 5. Measured and calculated $T_{b♀}(\lambda)$ relationship in the centimeter band for an isothermal lower atmosphere with $T = T_s = 650$°K: 1) $p_s = 63$ atm, 2) $p_s = 100$ atm, 3) $p_s = 187$ atm and a) $f_{H_2O} = 0.005$, b) $f_{H_2O} = 0$.

Such agreement can be obtained only for a lower water vapor content in the Venusian atmosphere. Thus, for $f_{H_2O} < 0.001$ these estimates lead to interconsistent pressures at the average surface level of $p_s = 100 \pm 20$ atm for $T_s =$ 650°K. The altitude of the zero level above the average surface is $h_0 = 51 \pm 3$ km. The thickness of the near-surface isothermal layer is 8-9 km in this model. From the considerations that have been presented it follows that if the relative water vapor content in the Venusian atmosphere is $f_{H_2O} \geq 0.005$, then the lower atmosphere of the planet should be in a state that is close to adiabatic. However, a smaller value of $f_{H_2O} < 0.005$ would favor the presence of a subadiabatic or isothermal layer at the surface.

In conclusion let us mention that in the model with an isothermal near-surface layer the calculated brightness temperature decreases markedly with an increase in wavelength in the decimeter band. This decrease agrees qualitatively with the results of the measurements of [11]; however, quantitatively the calculated $\bar{T}_{b♀}$ are still higher than the measurements at wavelengths of 30-70 cm.

Figure 6 shows the dependence, calculated by us, of the level of escape of the natural (thermal) Venusian radiation (the level at which $\tau_\lambda = 1$) on the wavelength λ for two atmosphere models. The increase in the H_λ values near $\lambda = 1.35$

cm for model I is caused by a water vapor absorption line. The same "anomaly" is, of course, absent in the H_λ values for the second model since $f_{H_2O} = 0$ for it.

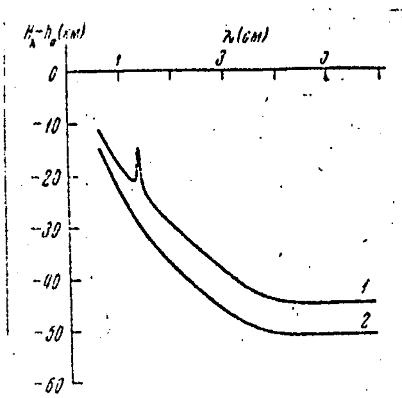


Figure 6. Escape level of natural emission of Venus (τ_λ = 1) for radio waves: 1) $f_{H_2O} = 0.005$; $f_{H_2O} = 0$.

We have also calculated the refraction of radio waves as they propagate through the entire thickness of the Venusian atmosphere. The index of refraction of the Venusian atmosphere in the centimeter and millimeter bands ($\lambda > 2$ mm) is determined from the formula

$$(n-1)\cdot 10^{-6} = K_1\frac{p_d}{T} + K_2\frac{\bar{e}}{T} + K_3\frac{\bar{e}}{T^2} \tag{8}$$

where the first term describes the contribution of the "dry" gases of the atmo- /155
sphere, and the second and third terms refer to the contribution of H_2O vapors; p_d and $\bar{e}$ are the corresponding partial pressures; $K_2 = 71.6$°K/mbar; $K_3 = 3.747\times10^5$ (°K)^2/mbar. The coefficient K_1 is 129.4°K/mbar for $f_{CO_2} = 0.95$ and $f_{N_2} + f_{oth.\,gas} = 0.045$; $K_1 = 132.7$°K/mbar for $f_{CO_2} = 1$ [22]. The calculation was made, using the formula [23]

$$\Delta R = -\int_{n_0}^{1} \operatorname{tg}\psi\frac{dn}{n}, \tag{9}$$

where ψ is the angle between the beam and grad n, n_0 is the value of the index of refraction n at the surface of Venus. Equation (9) is usually simplified by introducing a number of acceptable assumptions, the principal one being that surfaces of equal n are spherical surfaces, centered at the center of the planet. This makes it possible to express the angle ψ in terms of the index of refraction n, the radius r and the apparent (from the planet's surface) zenith angle θ, using the law of refraction for a system with spherical symmetry

$$n_0 r_0 \sin\theta = nr\sin\psi. \qquad (10)$$

Substituting (10) into (9) and replacing r by $r_0 + h$, we finally have for ΔR (in radians)

$$\Delta R = 10^{-6} n_0 r_0 \sin\theta \int_0^{N_0} \frac{(10^{-6}N+1)^{-1}\,dN}{\sqrt{(10^{-6}N+1)^2(r_0+h)^2-(10^{-6}N_0+1)^2 r_0^2\sin^2\theta}}. \qquad (11)$$

Here, $N = (n - 1) \cdot 10^6$ and $N_0 = (n_0 - 1) \cdot 10^6$. In the calculations the radius r_0 of Venus was assumed to be 6050 km.

The results of the calculation for the two Venusian atmosphere models chosen are shown in Table 1. The condition for superrefraction of radio waves is also indicated there.

TABLE 1

	50°	60°	70°	80°	Super-refraction condition
Model I (adiabatic, $f_{H_2O} = 0.005$, $p_s = 65$ atm, $T_s = 705$°K)	0°48'.9	1°11'.5	1°55'.3	4°23'.1	84.1°
Model II (isothermal, $f_{H_2O} = 0$, $p_s = 100$ atm, $T_s = 650$°K)	1°25'.5	2°06'	3°28'.2	10°50'.3	80.1°

Conclusions. Three independent estimates of the pressure and temperature of the Venusian atmosphere at the average surface level, based on radioastronomical measurements of the brightness temperature spectrum, polarization and radar reflection cross section, lead to two internally consistent models:

1) A model with an adiabatic near-surface atmosphere and the same relative water vapor content of $f_{H_2O} = 0.005$ at all altitudes. In this model the atmosphere pressure and temperature at the average Venusian surface level are equal to 65± 20 atm and 700± 50°K.

2) A model with an isothermal near-surface layer $T = T_s = 650$°K and a lower relative water vapor content of $f_{H_2O} = 0$. In this model the atmosphere pressure at the average surface level is 100± 20 atm. /156

Radioastronomical measurements indicate that the relative water vapor content in the Venusian atmosphere is closer to the lower limit, measured by the "Venus" series of space probes, than to the upper.

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